NEUTRINO-LESS DOUBLE BETA DECAY AND BEYOND THE STANDARD MODEL PHYSICS

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Abstract

A brief sketch is given of the present observational status and future prospects of the physics of neutrino mass, including a survey of the various theoretical schemes of neutrino mass generation. Emphasis is given to those which are motivated by present experimental hints from solar and atmospheric neutrinos, as well as from cosmological data related to the dark matter question. The conceptual importance of neutrino-less double beta decay as a distinctive signature of the Majorana character of neutrinos is stressed. Barring accidental cancellations this process gives the strongest laboratory constraint on neutrino mass.

1 Introduction

One of the most fundamental open issues of present-day particle physics is the determination and theoretical understanding of the question of whether neutrinos behave "trivially", as postulated in the standard model, or whether they have new properties. These include a wide variety of phenomena such as non-vanishing mass, oscillations, new interactions, neutrino decay modes and other exotic properties.

From the theoretical point of view, neutrinos are the only fermions in the standard model without right-handed partners. Although they are also the only electrically neutral fermions in the theory, lepton number cannot be broken by a Majorana mass term, because the electroweak breaking sector is kept to a minimum one consisting of just one Higgs doublet. While this cannot be excluded, it is rather mysterious why neutrinos are so special when compared with the other fundamental fermions. That this exceptional character of neutrinos is a circumstantial property of the standard model is better appreciated when one tries to extend the theory. Indeed, many unified extensions of the standard model, such as SO(10), do require the presence of

right-handed neutrinos in order to realize the larger symmetry, and also some extra Higgs representations. These are needed to break the extra symmetry and may naturally give rise to neutrino Majorana mass terms. Moreover, they provide a natural mechanism, called *seesaw*, to understand the relative smallness of neutrino masses [1, 2, 3]. In some of these extensions one can relate the V-A nature of the weak interaction to the observed smallness of the neutrino mass, and incorporate parity as a spontaneously broken symmetry. Unfortunately, the seesaw mechanism is just a general scheme which cannot, by itself, provide detailed predictions for neutrino masses and mixings. These will depend, among other factors, upon the structure of the Dirac-type entries, and also on the possible texture of the large Majorana mass term [4].

Although attractive, the seesaw mechanism is by no means the only way to generate neutrino masses. There are other attractive possibilities, some of which do not require the existence of any new gauge symmetries at a large mass scale. The extra particles required to generate the neutrino masses can have masses at scales accessible to present experiments [5]. Lepton number (or B-L), instead of being part of the gauge symmetry [6] is simply a global symmetry which is either broken explicitly or may be spontaneously broken [7]. The scale at which such a symmetry gets broken can be rather low, close to the weak scale [8, 9, 10]. Such a low scale for lepton number breaking could have important implications not only in astrophysics and cosmology but also in particle physics.

This large diversity of possible schemes and the lack of a fundamental theory for the Yukawa couplings imply that present theory is not capable of predicting the scale of neutrino masses any better than it can fix the masses of the other fermions, like that of the muon. As a result one should at this point turn to experiment.

1.1 Laboratory Limits on Neutrino Mass

There are several limits on neutrino masses that follow from observation. The laboratory bounds may be summarised as [11]

$$m_{\nu_e} \lesssim 5\,\mathrm{eV}, \quad \mathrm{m}_{\nu_\mu} \lesssim 250\,\mathrm{keV}, \quad \mathrm{m}_{\nu_\tau} \lesssim 23\,\mathrm{MeV} \tag{1}$$

and follow purely from kinematics. These are the most model-independent of the neutrino mass limits. The improved limit on the ν_e mass from beta decays was recently given by Lobashev [12], while that on the ν_τ mass follows from recent ALEPH data [13] on tau decays to five pions. A future tau factory should have enough sensitivity in order to substantially improve this ν_τ mass limit [14].

In addition, there are limits on neutrino masses that follow from the non-observation of neutrino oscillations [15]. They involve neutrino mass differences versus mixing, and disappear

Figure 1: Oscillation parameters probed at present and future neutrino experiments

in the limit of unmixed neutrinos. The present situation as well as future prospects to probe for neutrino oscillation parameters at long baseline experiments is given in Figure 1.

1.2 Neutrino-less Double Beta Decay

The most stringent limit on neutrino mass arises from the non-observation of $\beta\beta_{0\nu}$ decay, i.e. the process by which nucleus $(A, Z-2)$ decays to $(A, Z) + 2\ e^-$. This lepton number violating process would arise from Majorana neutrino exchange. Although highly favoured by phase space over the usual 2ν mode, the neutrino-less process proceeds only if the virtual neutrino is a Majorana particle. Its decay amplitude is proportional to a weighted average neutrino mass parameter

$$\langle m \rangle = \sum_{\alpha} {K_{e\alpha}}^2 m_\alpha \tag{2}$$

where the sum over α includes all light neutrinos. The negative searches for $\beta\beta_{0\nu}$ in ^{76}Ge and other nuclei leads to the limit [16]

$$\langle m \rangle \lesssim 1 - 2\ eV \tag{3}$$

depending somewhat on the nuclear matrix elements, characterising this process. Better sensitivity should be reached at the enriched germanium experiments. Although the limit in eq. (3) is rather stringent, the parameter $\langle m \rangle$ in eq. (2) can be very small even though the neutrino masses themselves are large. This will happen if there are strong cancellations between the contributions of different neutrino species. This is expected to happen accidentally or by virtue of some symmetry. For example, it happens in the case of a Dirac neutrino because the

Figure 2: $\beta\beta_{0\nu}$ decay and Majorana neutrinos.

lepton number symmetry [17] implies the automatic vanishing of $\langle m \rangle$. Even if all neutrinos are Majorana particles, the parameter $\langle m \rangle$ may differ substantially from the true neutrino masses m_α relevant for kinematical studies, which makes these studies therefore complementary.

The $\beta\beta_{0\nu}$ decay process may also be engendered through the exchange of scalar bosons, thus raising the question of which relationship the $\beta\beta_{0\nu}$ decay process bears with the Majorana nature of the neutrino mass. A simple but essentially rigorous proof was given [18] to show that, in a gauge theory of the weak interactions, a non-vanishing $\beta\beta_{0\nu}$ decay rate requires neutrinos to be Majorana particles, irrespective of which mechanism induces the process. This old argument (see fig. 2) relies on the fact that any Feynman graph inducing neutrino-less double beta decay can be closed, by W exchange, so as to produce a diagram generating a nonzero Majorana neutrino mass. This establishes a very deep connection between the two. Unfortunately, only in some special models, this may be translated into a useful lower limit on the neutrino masses. This happens, for example, if it is induced mainly by V-A or V+A currents, like in left-right symmetric models.

1.3 Hints for Neutrino Mass

In addition to the above limits there are some positive *hints* for neutrino masses that follow from the following astrophysical and laboratory observations.

The data collected up to now by Homestake and Kamiokande, as well as by the low-energy data on pp neutrinos from the GALLEX and SAGE experiments still pose a persisting puzzle [19, 20]. Comparing the data of GALLEX with the Kamiokande data indicates the need for a reduction of the ^{7} Be flux relative to the standard solar model expectation. The situation can be well represented by a plot in the plane defined by the ^{7} Be and ^{8} Be fluxes [21]. The one sigma region for these fluxes allowed by Kamioka and GALLEX data is obtained as the intersection of the region to the left of line labelled 91 with the region labelled KAMIOKA in Figure 3. The lines are normalised with respect to the reference solar model of Bahcall and collaborators, but the argument is model independent. If we include the Homestake data would

Figure 3: Allowed one sigma bands for ^{7} Be and ^{8} Be fluxes from all solar neutrino data

of course only aggravate the discrepancy, since it would, at face value, require a negative ^{7} Be flux, as can be seen from Figure 3! This strongly suggests that the solar neutrino problem is indeed a real problem, and that the simplest astrophysical solutions to the solar neutrino data are disfavoured, if not ruled out. This therefore suggests that one needs new physics in the neutrino sector if one wishes to account for the totality of solar neutrino data [22]. The most attractive possibility is to assume the existence of neutrino conversions involving very small neutrino masses around 10^{-3} eV, as seen in Figure 4 [23]. The region of parameters allowed by present experiments is given in ref. [24]. Note that the fits favour the non-adiabatic over the large mixing solution, due mostly to the larger reduction of the ^{7} Be flux found in the former.

Another possible solution of the solar neutrino problem is provided by long wavelength or just-so neutrino oscillations [25].

An apparent decrease in the expected flux of atmospheric ν_μ's relative to ν_e's arising from the decays of π's, K's and secondary muon decays produced in the atmosphere, has been observed in two underground experiments, Kamiokande and IMB, and possibly also at Soudan2 [26]. Although the predicted absolute fluxes of neutrinos produced by cosmic-ray interactions in the atmosphere are uncertain at the 20 % level, their ratios are expected to be accurate to within 5 %. This atmospheric neutrino deficit can be ascribed to neutrino oscillations. Combining these experimental results with observations of upward going muons made by Kamiokande, IMB and Baksan, and with the negative Frejus and NUSEX results [27] leads to the following range of neutrino oscillation parameters $\Delta m^2_{\mu\tau} \approx 0.005 - 0.5$ eV^2 and $\sin^2 2\theta_{\mu\tau} \approx 0.5$. Similar

Figure 4: Region of solar neutrino oscillation parameters allowed by experiment

analyses can be made for the case of ν_μ to ν_S and ν_μ to ν_e channels, where matter effects play a role [28]. Recent results from Kamiokande on higher energy neutrinos strengthen the case for an atmospheric neutrino problem [29] as shown in Figure 5. These data prefer maximum mixing between ν_μ and ν_τ as suggested by theoretical models [30].

1.4 Cosmology and Neutrino Mass

In addition to laboratory limits, there is a cosmological bound that follows from avoiding the overabundance of relic neutrinos [31]

$$\sum_i m_{\nu_i} \lesssim 95 \Omega h^2 \,\mathrm{eV} \tag{4}$$

This limit only holds if neutrinos are stable on cosmological time scales. There are many models where neutrinos decay into a lighter neutrino plus a Majoron [2],

$$\nu_\tau \to \nu_\mu + J \ . \tag{5}$$

Lifetime estimates in various Majoron models have been discussed in ref. [32]. These decays can be fast enough to obey the cosmological limits coming from the critical density requirement, as well as those that come from primordial big-bang nucleosynthesis [33]. Note also that, since these decays are *invisible*, they are consistent with all astrophysical observations.

Relic neutrinos may also disappear by annihilation into Majorons,

$$\nu_\tau \nu_\tau \to J J \ . \tag{6}$$

Figure 5: Region of atmospheric neutrino oscillation parameters from Kamiokande data.

Figure 6: Estimated ν_τ lifetime versus observational limits.

thus easily making it possible to obey cosmological nucleosynthesis limits [34].

Recent observations of cosmic background temperature anisotropies on large scales by the COBE satellite [35] seem to be in conflict with the simple cold dark matter model of structure formation, if one adopts as normalisation of the density fluctuation the cluster-cluster correlation data obtained e.g. from IRAS [36]. These data indicate the need for having more power on large scale. One of the simplest ways to achieve this is to postulate the existence of a hot *dark matter* component, contributing about 30% to the total mass density [37]. A good fit is provided by a massive neutrino, for example, a tau neutrino with mass in the few eV range. If such is the case one may expect the possibility of observing ν_e to ν_τ or ν_μ to ν_τ oscillations in the CHORUS and NOMAD experiments at CERN, as well as at the at the proposed P803 experiment at Fermilab [38]. This mass scale is also consistent with the recent preliminary indications that might favour the existence of neutrino oscillations from the LSND experiment [39].

Al alternative way to reconcile COBE and IRAS observations is the idea that a late decaying tau neutrino with mass in the MeV range can delay the epoch of radiation matter equality and will be discussed below [40].

2 Reconciling Present Hints.

Reconciling the present hints from astrophysics and cosmology in the framework of a consistent elementary particle physics model is not straightforward. It requires the existence of a neutrino with a mass scale which is clearly at odds with those inferred from the solar and atmospheric neutrino data discussed above. Indeed, if all the data are taken at face value they put an interesting theoretical puzzle whose possible resolutions will now be discussed.

2.1 Three Almost Degenerate Neutrinos

The only possibility to reconcile the above three observations in a world with just the three neutrinos of the standard model is if all of them have nearly the same mass ~ 2 eV [54]. This is clearly at odds with the simplest seesaw model where the neutrino masses scale as those of the up-type quarks. However, it is known that the general seesaw models have two independent terms giving rise to the light neutrino masses. The first is proportional to an effective triplet vacuum expectation value [41] which is expected to be small in left-right symmetric models [6]. Based on this fact one can in fact construct extended seesaw models where the main contribution to the light neutrino masses (~ 2 eV) is universal, due to a suitable horizontal

symmetry, while the splittings between ν_e and ν_μ explain the solar neutrino deficit and that between ν_μ and ν_τ explain the atmospheric neutrino anomaly [42].

If this all hints for neutrino mass are taken seriously and one adopts a minimal three neutrino scenario to explain them in terms of neutrino properties, it follows that the observability of neutrino-less double beta decay at the next generation of enriched germanium experiments should be possible.

2.2 Three Active plus One Sterile Neutrino

The alternative way to fit all the data is to add a fourth neutrino species which, from the LEP data on the invisible Z width, we know must be of the sterile type, call it ν_S . The first scheme of this type gives mass to only one of the three neutrinos at the tree level, keeping the other two mass-less [43]. In a seesaw scheme with broken lepton number, radiative corrections involving gauge boson exchanges will give small masses to the other two neutrinos ν_e and ν_μ [44]. However, since the singlet neutrino is super-heavy in this case, there is no room to account for the three hints discussed above.

The schemes which have been suggested to keep the sterile neutrino light require the use of a special symmetry [45, 30, 46]. Of these models, those containing only four neutral lepton states, with the fourth being the sterile neutrino ν_S , invoke the existence of additional Higgs bosons beyond that of the standard model, in order to generate radiatively the scales required for the solar and atmospheric neutrino conversions. In these models the ν_S either lies at the dark matter scale [45] or, alternatively, at the solar neutrino scale [30]. In the first case the atmospheric neutrino puzzle is explained by ν_μ to ν_S oscillations, while in the second it is explained by ν_μ to ν_τ oscillations. Correspondingly, the deficit of solar neutrinos is explained in the first case by ν_e to ν_τ oscillations, while in the second it is explained by ν_e to ν_S oscillations. In both cases it is possible to fit all observations together. However, in the first case there is a clash with the bounds from big-bang nucleosynthesis. In the latter case the ν_S is at the MSW scale so that nucleosynthesis limits are satisfied. They single out the non-adiabatic solution uniquely. Note also that the mixing angle characterising the ν_μ to ν_τ oscillations is nearly maximal, as suggested from Figure 5, taken from ref. [29]. Moreover, the model would naturally fit the recent preliminary hints of neutrino oscillations of the LSND experiment [39]. Another theoretical possibility is that all active neutrinos are very light, while the sterile neutrino ν_S is the single neutrino responsible for the dark matter [47].

As a last comment we mention that it has been argued that schemes where the hot dark matter is made up of two or more active neutrinos may provide a better fit of the data on

structure formation than models with a single such neutrino [48].

2.3 KeV Majoron and Late Decaying Tau Neutrino

Although we regard the late decaying tau neutrino solution very promising, it has not yet been as well explored as the mixed cold and hot dark matter picture of structure formation discussed above, which has been extensively studied in the last three years [37, 48]. This solution postulates an MeV scale tau neutrino which decays with lifetime of order of years. This lifetime value would fit nicely the required parameters and, on the other hand, would be perfectly achievable in elementary particle physics models where neutrino masses arise from the spontaneous violation of lepton number [2], as can be seen from fig. 6. There have also been speculations that the Majoron in these models could pick up a mass in the KeV range, as a result of gravitational effects [49] and that it would be the present-day cold dark matter particles [50]. This opens the possibility of a complete picture of cosmological dark matter which does not postulate two unrelated components of dark matter (like cold and hot) but successfully fits the observations from a common physics principle: the massive tau neutrino acquires mass from the spontaneous violation of lepton number and the resulting Majoron with mass in the KeV range plays the role of cold dark matter [51]. In contrast to the usual collisionless dark matter, these Majorons have a relatively strong self-interaction, needed in order to comply with nucleosynthesis constraints on the MeV tau neutrino, in the presence of the keV Majoron mass. This yields a rather different and interesting picture of structure formation. Electron and muon neutrinos would be very light, as required in order to account for the solar neutrino deficit through ν_e to ν_μ oscillations [10]. Super-symmetry with spontaneously broken R parity [9] provides a natural particle physics model for this scenario. Unfortunately this model cannot account for the atmospheric neutrino anomaly which would require the existence of a fourth sterile neutrino [52].

3 New Signatures.

The important role massive neutrinos can play in particle physics and cosmology and the existence of the hints discussed above should encourage one to continue the efforts to improve present laboratory neutrino mass limits, and/or to search for related signatures. Indeed, neutrino masses could be responsible for a wide variety of measurable implications at the laboratory. These new phenomena would cover an impressive range of energies, starting with the searches for anomalies in β decays [53], the searches for nuclear $\beta\beta_{0\nu}$ decays [16], the searches for neutrino oscillations at nuclear reactors and accelerators [15], especially those with long baseline,

which would help cross checking the present indications of an atmospheric neutrino anomaly and so on. It is not so often stressed that the signals related to neutrino properties beyond the standard model may sometimes show up even at the highest energies available at present-day particle colliders. In the following brief and biased survey of the situation I will give some examples of the latter.

3.1 Neutrino-less Double Beta Decay

If neutrinos are massive Majorana particles one expects neutrino-less double beta decays to take place at some level. Barring special cancellations it should be observable at enriched germanium experiments, if the quasi-degenerate neutrino scenario for the joint explanation of hot dark matter with the solar and atmospheric neutrino anomalies discussed in section 2.1 is realized in nature.

Gauge theories may also lead to new varieties of neutrino-less double beta decays, involving the *emission* of light scalar bosons, such as the Majoron, denoted by J [55] and of a related light scalar boson ρ

$$(A, Z-2) \to (A, Z) + 2\ e^- + J\ . \tag{7}$$

The emission of such weakly interacting light scalars would only be detected through their effect on the β spectrum. The simplest model leading to sizeable Majoron emission in $\beta\beta$ decays involving an isotriplet Majoron [56] leads to a new invisible decay mode for the neutral weak interaction gauge boson with the emission of light scalars,

$$Z \to \rho + J, \tag{8}$$

now ruled out by LEP measurements of the invisible Z width [57]. It has however been shown that a sizeable Majoron-neutrino coupling leading to observable emission rates in neutrino-less double beta decay can be reconciled with the LEP results in models where the Majoron is an isosinglet and lepton number is broken at a low scale [58]. An alternative possibility was discussed in ref. [59]. At the moment there is only a limit on the Majoron emitting neutrino-less double beta decay lifetime, leading to a bound on the Majoron-neutrino coupling of about 10^{-4} [60]. New varieties of neutrino-less double beta decay involving multiple *emission* of light scalars also exist [61] but it is hard to make the associated rates large enough to be experimentally observable [62].

Figure 7: Expected branching ratios for $\tau \to 3e$ (solid) and $\tau \to \mu\mu e$

3.2 Lepton Flavour Violation.

Another manifestation of neutrino properties beyond the standard model, such as neutrino masses or isosinglet neutral heavy leptons (NHLS), is the observability of lepton flavour violating (LFV) decays such as $\mu \to e\gamma$. Such decays are exactly forbidden in the standard model. Although these are a generic feature of models with massive neutrinos , they may proceed in models where neutrinos are strictly mass-less [63, 64, 65]. This is not only of conceptual importance but also practical. It means that the expected rate for LFV processes is necessarily suppressed due to the smallness of neutrino masses. Indeed, in these models the relevant constraints come from the universality of the weak interaction, which allows for decay branching ratios larger than the present experimental limits for a wide variety of LFV decays [66, 67]. The results are summarised in Table 1. As an illustration, Figure 7 gives the expectations for the three charged lepton decays of the tau, taken from ref. [67]. Clearly these branching ratios lie within the sensitivities of the planned tau and B factories, as shown in ref. [68].

The physics of rare Z decays nicely complements what can be learned from the study of rare LFV muon and tau decays. The stringent limits on $\mu \to e\gamma$ preclude any possible detectability at LEP of the corresponding $Z \to e\mu$ decay. However the decays with tau number violation, $Z \to e\tau$ or $\mu\tau$ can be large, as shown in Table 2. Similarly one can show that the CP violating Z decay asymmetries in these LFV processes can reach $\mathcal{O}$ (10^{-7}) [64]. Under realistic luminosity and experimental resolution assumptions, however, it is unlikely that one will be able to see these decays of the Z at LEP without a high luminosity option [69]. In any case,

Table 1: Allowed τ decay branching ratios

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channel	strength
$\tau \to e\gamma, \mu\gamma$	$\lesssim 10^{-6}$
$\tau \to e\pi^0, \mu\pi^0$	$\lesssim 10^{-6}$
$\tau \to e\eta^0, \mu\eta^0$	$\lesssim 10^{-6} - 10^{-7}$
$\tau \to 3e, 3\mu, \mu\mu e, etc.$	$\lesssim 10^{-6} - 10^{-7}$

Table 2: Allowed branching ratios for rare Z decays.

channel	strength
$Z \to N_\tau\ \nu_\tau$	$\lesssim 10^{-3}$
$Z \to e\tau$	$\lesssim 10^{-6} - 10^{-7}$
$Z \to \mu\tau$	$\lesssim 10^{-7}$

there have been dedicated experimental searches which have set good limits [70].

If the NHLS are lighter than the Z, they may also be produced directly in Z decays such as [71],

$$Z \to N_\tau + \nu_\tau \tag{9}$$

Note that the isosinglet neutral heavy lepton N_τ is singly produced, through the off-diagonal neutral currents which is characteristic of models containing doublet and singlet leptons [41]. Subsequent N_τ decays would then give rise to large missing momentum events, called zen-events. Theoretically attainable rates for such processes are large (see ref. [71]) and the present limits are summarized in Figure 8. The LEP limits follow from the negative searches for acoplanar jets and lepton pairs from Z decays at LEP, although some inconclusive positive hints have also been reported by the ALEPH collaboration [72].

Note also that there can also be large rates for lepton flavour violating decays in models with radiative mass generation [5]. For example, this is the case in the models proposed to reconcile present hints for neutrino masses [30, 45]. The expected decay rates may easily lie

Figure 8: Limits on $Z \to N\nu$ decays

within the present experimental sensitivities and the situation should improve at PSI or at the proposed tau-charm factories.

Finally, another possible type of LFV decays are those involving the emission of a Majoron, such as single Majoron emitting μ and τ decays [73]. These would be "seen" as bumps in the final lepton energy spectrum, at half of the parent lepton mass in its rest frame. They are present in models with spontaneous violation of R parity [9]. The allowed rates for these decays may fall within present experimental sensitivities [11]. As an illustration, I borrow Figure 9 from ref. [73]. This example also illustrates how the search for rare decays can be a more sensitive probe of neutrino properties than the more direct searches for neutrino masses, and therefore complementary. Moreover, they are ideally studied at a tau-charm factory [68].

3.3 Invisibly Decaying Higgs Bosons.

Nonstandard neutrino properties may affect even the electroweak breaking sector. For example, many extensions of the lepton sector seek to give masses to neutrinos through the spontaneous violation of an ungauged U(1) lepton number symmetry, thus implying the existence of a physical Goldstone boson, called Majoron [7]. As already mentioned above this is consistent with the measurements of the invisible Z decay width at LEP if the Majoron is (mostly) a singlet under the $SU(2) \otimes U(1)$ gauge symmetry.

Although the original Majoron proposal was made in the framework of the minimal seesaw

Figure 9: Allowed branching ratios for $\tau \rightarrow e + J$ versus m_{ν_τ}

model, and required the introduction of a relatively high energy scale associated to the mass of the right-handed neutrinos , there are many attractive theoretical alternatives where lepton number is violated spontaneously at the weak scale or lower. In this case although the Majoron has very tiny couplings to matter and the gauge bosons, it can have significant couplings to the Higgs bosons. The latter can, as a result, decay with a substantial branching ratio into the invisible mode [8]

$$h \rightarrow J \ + \ J \tag{10}$$

The production and subsequent decay of a Higgs boson which may decay visibly or invisibly involves three independent parameters: its mass M_H, its coupling strength to the Z, normalised by that of the standard model, ϵ^2, and its invisible decay branching ratio. The LEP searches for various exotic channels can be used in order to determine the regions in parameter space that are already ruled out [74]. The result is shown in Figure 10 taken from the first paper in ref. [75].

Another mode of production of invisibly decaying Higgs bosons is that in which a CP even Higgs boson is produced at LEP in association with a massive CP odd scalar. This production mode is present in all but the simplest Majoron model and the corresponding LEP limits on the relevant parameters are given in ref. [76].

Finally, the invisible decay of the Higgs boson may also affect the strategies for searches at higher energies. For example, the ranges of parameters that can be covered by LEP2 searches for a total integrated luminosity of 500 pb^{-1} and various centre-of-mass energies have been

Figure 10: Region in the ϵ^2 vs. m_H that can be excluded by the present LEP1 analyses (solid curve). Also shown are the LEP2 extrapolations (dashed).

given in Figure 10. Similar analysis were made for the case of a high energy linear e^+e^- collider (NLC) [77], as well as for the LHC [78].

3.4 Conclusion

Present cosmological and astrophysical observations, as well as theory, suggest that neutrinos may be massive. Existing data do not preclude neutrinos from being responsible for a wide variety of measurable implications at the laboratory. It is therefore quite worthwhile to keep pushing the underground experiments, for any possible confirmation of neutrino masses. These includes experiments with enriched germanium looking for neutrino-less $\beta\beta$ decays, solar neutrino experiments GALLEX and SAGE, as well as Superkamiokande, Borexino, and Sudbury. The same can be said of the ongoing studies with atmospheric neutrinos, which may be cross-checked at long baseline neutrino oscillation searches. Similarly, a new generation of experiments capable of more accurately measuring the cosmological temperature anisotropies at smaller angular scales than COBE, would be good probes of different models of structure formation, and presumably shed further light on the possible role of neutrinos as dark matter.

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